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When are extremely metal-deficient galaxies extremely metal-deficient?

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ABSTRACT

Extremely metal-deficient (XMD) galaxies, by definition, have oxygen abundances $\leqslant$ 1/10 solar, and form a very small fraction of the local gas-rich, star-forming dwarf galaxy population. We examine their positions in the luminousity–metallicity (L–Z) and mass-metallicity (M–Z) planes, with respect to the L–Z and M–Z relations of other gas-rich, star-forming dwarf galaxies, viz., blue compact galaxies (BCGs) and dwarf irregular (dI) galaxies. We find that while the metallicities of some low-luminousity XMD galaxies are consistent with those expected from the L–Z relation, other XMD galaxies are deviant, and more so as the luminousity and/or metal-deficiency increases. We determine the 95 per cent confidence interval around the L–Z relation for BCGs, and find that its lower boundary is given by 12 + log(O/H) = –0.177 M_B + 4.87. We suggest that a galaxy should be regarded as XMD, in a statistically significant manner, only if it lies below this boundary in the L–Z plane. Of our sample of XMD galaxies, we find that more than half are XMD by this criterion, and in fact, nine of the galaxies lie below the 99.5 per cent confidence interval about the L–Z relation.

We also determine the gas mass fractions and chemical yields of galaxies in all three samples. We find that the effective chemical yield increases with increasing baryonic mass, consistent with what is expected if outflows of metal-enriched gas are important in determining the effective yield. XMD galaxies have lower effective yield than BCG/dI galaxies of similar baryonic mass. This suggests that some process, peculiar to XMD galaxies, has resulted in their low measured metallicities. Motivated by the fact that interactions are common in XMD galaxies, we suggest that improved (tidally-driven) mixing of the interstellar media (ISM) in XMD galaxies leads to a lowering of both, the measured metallicity and the calculated effective yield. In isolated dwarf galaxies, the outer parts of the stellar envelope probably do not participate in the star formation, but are still generally included in the calculation of effective yield. This results in an overestimate of the effective yield. We suggest that XMD galaxies are deviant from the L–Z relation because of a combination of being gas-rich (i.e., having processed less gas into stars) and having more uniform mixing of metals in their ISM.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: evolution

1 INTRODUCTION

Extremely metal-deficient (XMD) galaxies are defined as galaxies with interstellar medium (ISM) oxygen abundances less than or equal to 0.1 $Z_\odot$, i.e., 12 + log(O/H) $\leqslant$ 7.65 (e.g., Kunth & Ostlin 2000; Kniazev et al. 2003; Pustilnik & Martin 2007; Brown, Kewley & Geller 2008). Such metallicities are more typical of primeval galaxies at high red-shifts, and it is not firmly established that why such low-metallicity star-forming galaxies exist in the local Universe. Their low metallicities could be due to (1) slow chemical evolution, i.e., a lower than usual time-averaged star formation rate, (2) infall of metal-poor gas, (3) preferential loss of metal-enriched gas through galactic winds. While XMD galaxies form a very small fraction of the gas-rich, star-forming dwarf galaxy population (i.e., blue compact and dwarf irregular galaxies), the mere existence of a local population of chemically-unevolved galaxies is noteworthy. Do these galaxies represent a separate population, or are they, merely, the low-metallicity tail of the metallicity distribution of galaxies?

In trying to address this question, a useful starting point is to note that for galaxies, in general, metallicity corre-

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lates with both luminousity and mass (e.g., Skillman, Kennicutt & Hodge 1989; Tremonti et al. 2004; Lee et al. 2006). Possible reasons for such a correlation are (1) that the star formation efficiency increases with mass, so that low-mass galaxies end up converting a smaller fraction of their mass into stars, and hence having lower metallicities, or (2) that massive galaxies, by virtue of having deeper potential wells, are more capable of retaining their metals instead of losing them through enriched galactic winds. The relative importance of these two factors is not well established. For example, Brooks et al. (2007) show that star formation efficiencies, regulated by stellar feedback, lead to low metallicity for low-mass galaxies. On the other hand, Tremonti et al. (2004), from a study of star-forming Sloan Digital Sky Survey (SDSS) galaxies, find evidence in favour of the correlation being driven by decreasing metal-loss efficiency with increasing mass [but, see also Lee et al. (2006) and Vale Asari et al. (2009), who argue against this]. In any case, since galaxy metallicity is known to correlate with both the luminousity and mass, the question regarding the nature of XMD galaxies is that are these galaxies outliers with respect to the luminousity–metallicity (L–Z) or mass–metallicity (M–Z) correlations? Similarly, does a comparison of the effective chemical yields of XMD and other dwarf galaxies give some clue as to why XMD galaxies are metal-poor?

To answer these questions, we have constructed a sample of XMD galaxies, along with comparison samples of the two major classes of gas-rich, star-forming dwarf galaxies, viz., blue compact galaxies (BCGs) and dwarf irregular (dI) galaxies. We derive L–Z and M–Z correlations for each of the BCG and dI samples, and see where XMD galaxies lie with respect to these correlations. We also calculate and compare their effective chemical yields with BCGs and dI galaxies. To the best of our knowledge, this is the first derivation of the M–Z relations for BCG galaxies, as a class.

Our paper is divided into the following sections. We describe our samples in Section 2. The derived L–Z and M–Z relations and chemical yields are given in Section 3. We discuss and summarise our results in Section 4.

2 SAMPLES

We have selected a sample of 59 local ($V_{\rm hel} < 4500$ km s^{-1}) BCGs from emission-line galaxies in the SDSS Data release 3 (DR3), whose abundance measurements are published by Izotov et al. (2006a). We have chosen galaxies with compact optical morphology, as seen in their g-band SDSS images, for our BCG sample. We have no bias towards metallicity in our selection, except that we have chosen only those galaxies for which oxygen abundances, given by 12 + log(O/H), have been determined to within 0.1 dex. However, very few BCGs were dropped due to this cut-off on accuracy of determined metallicities, and we confirmed that it is not introducing any luminousity bias in our sample. Also, note that the majority of the galaxies have much more accurate determinations of oxygen abundances than this. Four of these BCGs have metallicities that fall in the XMD regime. We have calculated the B and R-band magnitudes of the galaxies from their SDSS g and r magnitudes, using the formulae derived by Lupton (2005), which are given on the SDSS web-site. The parameters of galaxies, in our BCG sample, are given in Table 1.

We have searched the literature for dI galaxies with known oxygen abundances and optical magnitudes, and selected 32 galaxies for representative dI sample. All of them are well-studied, and have been classified as dIs by other researchers and/or NASA/IPAC Extragalactic Database (NED). Relevant parameters for this sample are given in Table 2. Eight of these dIs have metallicities that fall in the XMD regime. For XMD galaxies also, we searched the literature, and chose known nearby (v_{hel} <4500 km s^{-1}) XMD galaxies for our sample. Table 3 gives the corresponding parameters for the 31 XMD galaxies in our sample. Oxygen abundances of all BCGs, XMD and dI galaxies, except UGC 12613, UGC 4117, are determined by the more accurate 'direct' method.

Stellar masses were computed using formulae given by Bell & de Jong (2001), using their formation epoch: bursts model. The mass-to-luminousity ratio was computed using extinction-corrected B-V colours, whenever available. For galaxies where the B-V colour was not available, we used extinction-corrected B-R colours. For galaxies for which both B-V and B-R colours are available, ratios found from B-V colour were systematically higher than those obtained from B-R colour by a factor of ∼1.38. While this is within the variations in the model mass-to-luminousity ratio given by Bell & de Jong (2001), we have none the less, for consistency, scaled the stellar masses obtained from the B-R by 1.38. Since CO emission is not detected, or detected at a very low level, in most of the dwarf galaxies (e.g., Taylor, Kobulnicky & Skillman 1998), we have neglected the contribution of molecular gas for our samples, assuming that it is small. We have, however, scaled H I masses by a factor of 1.33, to account for He.

Following Lee et al. (2003) and Vaduvescu, McCall & Richer (2007), the linear fits for the L–Z and M–Z correlations, of each of the dI and BCG samples, were obtained using geometric mean functional relationship, so that a fair comparison between relations derived here and those derived in these earlier works can be drawn. This method assumes similar dispersions in both observables, and is apt for use when there are uncertainties in measurements of both variables.

3 RESULTS

The correlations of oxygen abundance [12 + log(O/H)] with B-band absolute magnitude (L–Z), stellar mass (M_*–Z), gas mass (M_{gas}–Z) and baryonic mass (M_{bary}–Z) for BCG and dI samples are given in Table 4. We also provide the correlations of nitrogen abundance with B-band absolute magnitude (L–N) and stellar mass (M_*–N), for both samples, in the same Table. These correlations, along with the data points themselves, are shown in Fig. 1. To the best of our knowledge, this is the first derivation of the mass–metallicity relations for BCGs. We find that the L–Z and M–Z correlations for BCGs are dIs are, by and large, similar, except that the L–Z relation for BCGs is slightly steeper than that of dIs. Also, the two L–Z relations are slightly offset, such that for a given metallicity, BCGs are slightly more luminous than dIs. The same trends, in L–Z relation, were noted earlier by Lee

Name	m_B	12 + log(O/H)	log(N/O)	H I flux (Jy kms^{-1})	References
SDSS J002425.94+140410.3	16.41	8.39 ± 0.07	–1.48 ± 0.09		
SDSS J005319.63–102411.8	16.60	8.14 ± 0.10	–1.00 ± 0.13		
SDSS J011914.27–093546.4	17.88	7.61 ± 0.04	–1.38 ± 0.07	1.5	1
UM 323	16.16	7.96 ± 0.04	–1.50 ± 0.06	2.4	2
SDSS J021852.90–091218.7	18.67	7.89 ± 0.03	–1.49 ± 0.06		
SDSS J023145.99–090847.6	17.05	8.16 ± 0.03	–1.54 ± 0.05		
SDSS J024815.93–081716.5	16.04	7.98 ± 0.02	–1.55 ± 0.03		
SDSS J025346.36–072343.6	16.75	7.89 ± 0.03	–1.48 ± 0.04	1.5	1
SDSS J025426.12–004122.6	17.61	8.06 ± 0.05	–1.46 ± 0.07		
SDSS J082555.52+353231.9	17.93	7.42 ± 0.03	–1.50 ± 0.07	0.3	3
SDSS J082718.07+460203.0	15.79	8.23 ± 0.07	–1.42 ± 0.09		
MRK 0627	16.01	8.24 ± 0.04	–1.34 ± 0.06		
SDSS J085920.83+005142.1	17.26	8.09 ± 0.06	–1.32 ± 0.08		
SDSS J091028.77+071117.9	16.67	7.63 ± 0.03	–1.41 ± 0.05	2.0	4
UGCA 154	15.18	8.22 ± 0.07	–1.23 ± 0.10		
MCG +09–15–115	16.08	8.12 ± 0.05	–1.28 ± 0.06		
MRK 1416	16.32	7.89 ± 0.02	–1.50 ± 0.03	2.0	5
SBS 0926+606A	16.22	7.99 ± 0.02	–1.46 ± 0.04	1.3	6
UGCA 184	16.11	8.04 ± 0.02	–1.44 ± 0.03	2.2	5
SDSS J095241.42+020758.1	17.71	7.92 ± 0.04	–1.42 ± 0.06		
UGCA 208	15.35	8.30 ± 0.08	–1.28 ± 0.11		
SDSS J103137.27+043422.0	16.40	7.70 ± 0.04	–1.35 ± 0.11		
MRK 1434	16.59	7.79 ± 0.03	–1.51 ± 0.06		
SBS 1037+494	16.93	8.01 ± 0.03	–1.49 ± 0.04	1.9	7
SDSS J104456.00+004433.4	16.79	7.82 ± 0.03	–1.45 ± 0.05		
CGCG 010–041	15.83	8.38 ± 0.10	–1.39 ± 0.13	5.4	8
SDSS J105741.94+653539.7	16.70	8.29 ± 0.04	–1.45 ± 0.06		
TOLOLO 1108+098	15.47	8.15 ± 0.08	–1.46 ± 0.11	2.8	2
SDSS J112526.75+654607.2	17.88	7.81 ± 0.05	–1.60 ± 0.08		
MRK 1446	16.07	8.13 ± 0.04	–1.51 ± 0.06	0.9	7
SDSS J112742.97+641001.4	17.52	8.18 ± 0.10	–1.36 ± 0.13		
SDSS J113341.19+634925.9	17.59	7.97 ± 0.04	–1.49 ± 0.06		
UM 454	16.40	7.94 ± 0.07	–1.28 ± 0.09	0.8	2
UM 461	16.05	7.81 ± 0.02		3.0	2
UM 462	14.45	7.82 ± 0.02	–1.49 ± 0.03	5.6	2
UM 463	17.66	7.81 ± 0.03	–1.49 ± 0.05		
SBS 1205+557	17.26	7.92 ± 0.04	–1.53 ± 0.06	0.2	7
MRK 1313	16.11	8.19 ± 0.06	–1.46 ± 0.08	1.6	2
SBS 1211+540	17.30	7.65 ± 0.03	–1.58 ± 0.08	0.6	7
HARO 06	15.21	8.25 ± 0.07	–1.29 ± 0.08	2.1	9
SBS 1222+614	14.95	8.00 ± 0.02	–1.55 ± 0.04	2.8	10
VCC 1744	17.12	7.82 ± 0.03	–1.51 ± 0.05		
SDSS J124159.34–034002.4	18.47	7.68 ± 0.04	–1.39 ± 0.06		
UM 538	17.51	8.02 ± 0.04	–1.42 ± 0.06	0.2	9
MRK 1480	16.31	8.04 ± 0.05	–1.44 ± 0.07	2.8	7
SDSS J135030.82+622649.0	17.44	7.91 ± 0.05	–1.41 ± 0.07		
UM 618	17.92	7.97 ± 0.06	–1.48 ± 0.08	0.2	9
SBS 1423+517	16.61	8.06 ± 0.05	–1.34 ± 0.06	0.9	7
SBS 1428+457	15.50	8.40 ± 0.05	–1.49 ± 0.06	4.1	7
SDSS J143053.51+002746.2	16.67	8.15 ± 0.03	–1.61 ± 0.05		
SBS 1453+526	17.13	8.02 ± 0.07	–1.35 ± 0.09	0.7	7
SDSS J153704.18+551550	15.50	8.08 ± 0.02	–1.61 ± 0.03		
SDSS J161623.53+470202.3	16.69	7.98 ± 0.04	–1.56 ± 0.06		
SDSS J165730.29+384122.9	17.03	7.94 ± 0.04	–1.54 ± 0.06		
SDSS J171236.63+321633.4	17.95	7.89 ± 0.03	–1.55 ± 0.06		
MRK 0894	15.67	8.44 ± 0.10	–1.14 ± 0.13		
SDSS J211942.38–073224.3	17.60	7.98 ± 0.05	–1.43 ± 0.07	8.4	8
SDSS J223036.79–000636.9	17.38	7.66 ± 0.04		1.3	1
UM 158	16.90	8.10 ± 0.05	–1.40 ± 0.07		

Table 1. Parameters of galaxies in the BCG sample. **References** (for H I fluxes): 1. Geha et al. (2006); 2. Smoker et al. (2000); 3. Chengalur et al. (2006); 4. Hogg et al. (1998); 5. Thuan et al. (1999); 6. Pustilnik et al. (2002); 7. Huchtmeier, Krishna & Petrosian (2005); 8. Doyle et al. (2005); 9. Salzer et al. (2002); 10. Huchtmeier et al. (2007)

Name	m_B	12 + log(O/H)	log(N/O)	H I flux (Jy kms^{-1})	References
UGC 12894	16.55	7.56 ± 0.04	–1.54 ± 0.08	4.5	1, 2, 3
WLM	11.30	7.83 ± 0.06	–1.49 ± 0.08	294.0	4, 5, 6
UGC 00300	15.86	7.80 ± 0.03	–1.50 ± 0.11	4.5	7, 7, 8
ESO 473– G 024	16.04	7.45 ± 0.03	–1.43 ± 0.03	5.7	9, 10, 11
IC 1613	10.25	7.62 ± 0.05	–1.13 ± 0.18	482.0	4, 12, 13
UGC 00685	14.20	8.00 ± 0.03	–1.45 ± 0.08	11.8	1, 12, 14
UGC 01104	14.41	7.94 ± 0.04	–1.67 ± 0.07	11.2	1, 2, 15
UGCA 020	15.78	7.58 ± 0.03	–1.57 ± 0.11	10.2	16, 16, 16
ESO 245– G 005	12.60	7.70 ± 0.10	–1.27 ± 0.10	87.3	17, 12, 18
UGC 02023	13.88	8.01 ± 0.02	–1.35 ± 0.06	18.7	1, 2, 19
UGC 03174	15.02	7.83 ± 0.09		18.6	7, 7, 8
ESO 489– G?056	15.70	7.49 ± 0.10	–1.35 ± 0.20	2.8	9, 12, 20
UGC 03647	14.67	8.07 ± 0.04	–1.28 ± 0.07		1, 2
UGC 03672	15.40	8.01 ± 0.04	–1.64 ± 0.12	15.4	1, 2, 8
UGC 03974	13.62	7.92 ± 0.06		61.0	21, 22, 23
UGC 4117	15.34	7.89 ± 0.10	–1.52 ± 0.15	4.1	1, 2, 24
Holmberg II	11.54	7.71 ± 0.13		267.0	4, 25, 26
UGC 04483	15.29	7.56 ± 0.03	–1.57 ± 0.07	13.6	27, 12, 28
Sextans B	12.07	7.84 ± 0.05	–1.46 ± 0.06	102.4	4, 29, 14
UGC 05423	14.42	7.98 ± 0.10	–1.26 ± 0.25	3.8	21, 30, 31
NGC 4214	10.32	8.22 ± 0.05	–1.30 ± 0.15	261.7	4, 32, 19
UGCA 292	15.86	7.30 ± 0.03	–1.45 ± 0.07	17.6	4, 12, 33
NGC 4789A	14.20	7.67 ± 0.06	–1.68 ± 0.13	105.0	4, 12, 34
UGC 08091	14.70	7.65 ± 0.06	–1.51 ± 0.07	9.7	4, 12, 33
UGCA 357	15.63	8.04 ± 0.04	–1.55 ± 0.14	13.2	7, 7, 8
UGC 08651	14.45	7.85 ± 0.04	–1.60 ± 0.09	11.4	35, 12, 28
UGC 09128	14.46	7.75 ± 0.05	–1.80 ± 0.12	13.9	1, 12, 19
UGC 09240	13.31	7.95 ± 0.03	–1.60 ± 0.06	24.6	1, 12, 36
UGC 9992	14.86	7.88 ± 0.12	–1.26 ± 0.19	11.8	1, 2, 19
NGC 6822	9.81	8.11 ± 0.05	–1.60 ± 0.10	2266.0	4, 12, 37
UGC 12613	12.50	7.93 ± 0.14	–1.24 ± 0.15		1, 12
UGC 12713	14.91	7.80 ± 0.06	–1.54 ± 0.11	10.8	1, 2, 38

Table 2. Parameters of galaxies in the dI sample. **References** (m_B, 12 + log(O/H) and log(N/O), H I fluxes): 1. van Zee (2000); 2. van Zee & Haynes (2006); 3. Staveley-Smith, Davies & Kinman (1992); 4. Hunter & Elmegreen (2006); 5. Lee, Skillman & Venn (2005); 6. Kepley et al. (2007); 7. van Zee, Haynes & Salzer (1997); 8. van Zee et al. (1997a), 9. Parodi, Barazza & Binggeli (2002); 10. Skillman, Cote & Miller (2003); 11. Warren, Jerjen & Koribalski (2006); 12. van Zee, Skillman & Haynes (2006); 13. Silich et al. (2006); 14. Hoffman et al. (1996); 15. Smoker et al. (2000); 16. van Zee et al. (1996); 17. Makarova et al. (2005); 18. Cote et al. (1997); 19. Swaters et al. (2002); 20. Pustilnik & Martin (2007); 21. Makarova (1999); 22. Lee, Zucker & Grebel (2007); 23. Walter & Brinks (2001); 24 O'Neil (2004); 25. Lee et al. (2003); 26. Bureau & Carignan (2002); 27. Gil de Paz, Madore & Pevunova (2003); 28. Huchtmeier, Karachentsev & Karachentseva (2003); 29. Kniazev et al. (2005); 30. Miller & Hodge (1996); 31. Walter et al. (2007); 32. Lee et al. (2006); 33. Young et al. (2003); 34. Carignan & Purton (1998); 35. Makarova et al. (1998); 36. Springob et al. (2005); 37. de Blok & Walter (2006); 38. Noordermeer et al. (2005).

et al. (2004) for their sample of H II galaxies, who suggested that the ongoing star burst has temporarily enhanced the luminousity of these galaxies compared to dIs. Consistent with this suggestion, the M_*–Z correlations for dIs and BCGs are much better matched. M_{gas}–Z and M_{bary}–Z relations for dIs and BCGs also match within their error bars. Nevertheless, there seems to be a suggestion (especially, from the M_*–Z plots and data points) that dIs are slightly metal-poor than BCGs, for a given mass. Vaduvescu et al. (2007) also made a similar observation for their dI sample and a small sample of Virgo Cluster blue compact dwarf (BCD) galaxies, and found that for a given metallicity, BCD galaxies have lower baryonic masses than dI galaxies. The correlations using nitrogen, as a metallicity tracer, are similar to those derived from the oxygen abundance. The published L–Z and M–Z relations of dIs (viz., Lee et al. 2003; van Zee & Haynes 2006; Lee et al. 2006; Vaduvescu et al. 2007) and L–Z relation of H II galaxies (Lee et al. 2004) are quite close to those we derive from our samples.

As for our XMD sample, while some of the low-luminousity galaxies lie along the derived L–Z and M–Z relations, other XMD galaxies are deviant, and more so at larger masses and/or lower metallicities (Fig. 1). In order to find the statistical significance of these deviations, we have drawn 95 per cent confidence interval about the L–Z relation for BCGs, along with data points of XMD galaxies, as shown in Fig. 2. Note that the confidence interval, around the regression line, was computed using standard formulae (see, e.g., Montgomery, Peck & Vining 2006). While the regression line, itself, was computed using the Geometric Mean Regression (GMR), this confidence interval was calculated assuming that 12 + log(O/H) is the independent variable. However, the width of the confidence interval, computed as above, should also be a sufficient measure of the confidence interval around the GMR.

Name	m_B	12 + log(O/H)	log(N/O)	H I flux (Jy kms^{-1})	References
UGC 772	13.73	7.24 ± 0.05		5.3	1,2,3
HS 0122+0743	15.50	7.60		7.6	4,5,4
SDSS J0133+1342	18.42	7.60 ± 0.03		0.10	6,7,4
UM 133	15.57	7.63 ± 0.02		4.2	8,9,10
KUG 0201–103	17.35	7.56 ± 0.03			6,2
KUG 0203–100	15.15	7.61 ± 0.09		12.2	6,7,4
SDSS J030149.02–005257.3	18.64	7.52 ± 0.06			6,2
SBS 0335–052W	19.14	7.12 ± 0.03	–1.60 ± 0.04	0.86	11,12,12,13
SBS 0335–052E	16.95	7.29 ± 0.02	–1.53 ± 0.03	0.61	11,14,14,13
HS 0846+3522	18.19	7.65		0.10	6,4,4
SDSS J091159.43+313535.9	18.01	7.51 ± 0.14			6,2
I Zw 18	16.06	7.25 ± 0.04	–1.64 ± 0.07	2.97	15,16,16,17
KUG 0937+298	16.19	7.65 ± 0.04	–1.49	2.05	6,18,18,4
SBS 0940+544	17.23	7.43 ± 0.01	–1.61 ± 0.03		8,19,19
DDO 68	14.60	7.14 ± 0.03		28.9	20,2,3
HS 1013+3809	15.99	7.59		1.51	6,4,4
HS 1033+4757	17.76	7.65		1.32	6,4,4
SDSS J1044+0353	17.39	7.46 ± 0.03	–1.69 ± 0.08		6,16,16
HS 1059+3934	17.63	7.62		1.39	6,4,4
SDSS J1105+6022	16.46	7.64 ± 0.04		2.48	6,7,4
SBS 1116+517	17.13	7.51 ± 0.04		1.31	6,7,21
SDSS J1121+0324	16.89	7.64 ± 0.08		2.67	6,7,4
SBS 1129+576	16.40	7.41 ± 0.08	–1.52	3.9	6,22,22,23
SBS 1159+545	18.39	7.49 ± 0.01	–1.58 ± 0.04		6,19,19
Tol 1223–359	17.58	7.54 ± 0.01	–1.60 ± 0.02	2.13	8,24,24,4
KISSR 1490	19.34	7.56 ± 0.07	–1.41		6,25,25
SBS 1415+437	15.47	7.61 ± 0.01	–1.56 ± 0.02	5.40	8,26,26,21
HS 1442+4250	15.61	7.63 ± 0.02	–1.44 ± 0.04	7.05	8,27,27,4
HS 1704+4332	18.41	7.55		0.24	8,4,4
SDSS J210455.31-003522.2	18.04	7.26 ± 0.03		2.0	6,28,3
HS 2134+0400	19.30	7.44		0.12	29,29,4

Table 3. Parameters of the studied XMD galaxies. **References**: 1. Patterson & Thuan (1996); 2. Izotov & Thuan (2007); 3. Ekta, Chengalur & Pustilnik (2008); 4. Pustilnik & Martin (2007); 5. Ugryumov et al. (2003); 6. SDSS; 7. Kniazev et al. (2003); 8. Gil de Paz et al. (2003); 9. Kniazev et al. (2001); 10. Smoker et al. (2000); 11. Pustilnik, Pramskij & Kniazev (2004); 12. Izotov, Thuan & Guseva (2005); 13. Ekta, Pustilnik & Chengalur (2009); 14. Izotov et al. (2006c); 15. Papaderos et al. (2002); 16. Izotov et al. (2006a); 17. van Zee et al. (1998); 18. Lee, Salzer & Melbourne (2004); 19. Izotov & Thuan (1999); 20. Pustilnik, Kniazev & Pramskij (2005); 21. Huchtmeier et al. (2005); 22. Guseva et al. (2003a); 23. Ekta, Chengalur & Pustilnik (2006); 24. Izotov et al. (2004); 25. Melbourne et al. (2004); 26. Guseva et al. (2003c); 27. Guseva et al. (2003b); 28. Izotov et al. (2006b); 29. Pustilnik et al. (2006)

Fig. 2 also shows the metallicity criterion (viz., 12 + log(O/H) $\leqslant$ 7.65) used for defining XMD galaxies. We note that for all BCGs with $M_B > -15.7$, a metallicity of 12 + log(O/H) = 7.65 lies within the 95 per cent confidence interval about the L–Z relation. Conversely, BCGs brighter than $M_B \sim -15.7$ can have 12 + log(O/H) = 7.65, but still be outliers with respect to the L–Z relation. The lower bound to the 95 per cent confidence interval is given by $Z = -0.177\ M_B + 4.87$, and only those galaxies which have metallicities below this are 'extremely metal-deficient' in a statistically significant manner. We note that the choice of the 95 per cent confidence interval is somewhat arbitrary, but suggest it, none the less, as a reasonable working definition. Of our sample of XMD galaxies, we find that more than half (17 of the 31) are classified as XMD by this definition, and in fact, nine of them lie outside the 99.5 per cent confidence interval about the L–Z relation. Further, it remains true that galaxies with 12 + log(O/H) $\leqslant$ 7.65 are significantly more metal-deficient than the gas in the solar neighbourhood, and in this sense, they can still be regarded as 'extremely metal-deficient'.

The nitrogen-to-oxygen abundance ratio [log(N/O)] is plotted against oxygen abundance in Fig. 3. We find a moderate correlation between log(N/O) and 12 + log(O/H) for a combined sample, consisting of our BCG and XMD BCG samples (correlation coefficient is 0.51 ± 0.07). While it is well-known that these quantities correlate at high metallicities [12 + log(O/H) above 8.3, see, e.g., Henry, Edmunds & Koppen (2000)] it is interesting that we find a correlation, even though most of our galaxies are below this metallicity. However, consistent with the findings in Izotov et al. (2006a), the N/O ratio does show signs of flattening at low metallicities, i.e., 12 + log(O/H) below 7.4.

We have, so far, been considering the metallicity of a galaxy, which, in some sense, is a measure of the amount of its past star formation activity. Specifically, in a closed-box model (assuming, further, that the delay between star formation and the release of metal-enriched gas is negligible, and that the gas is well-mixed) the metallicity of a galaxy is related to its gas mass fraction (μ_{gas}) and the 'chemical yield' (p) by

$$Z = p \ln(1/\mu_{\rm gas}) \qquad (1)$$

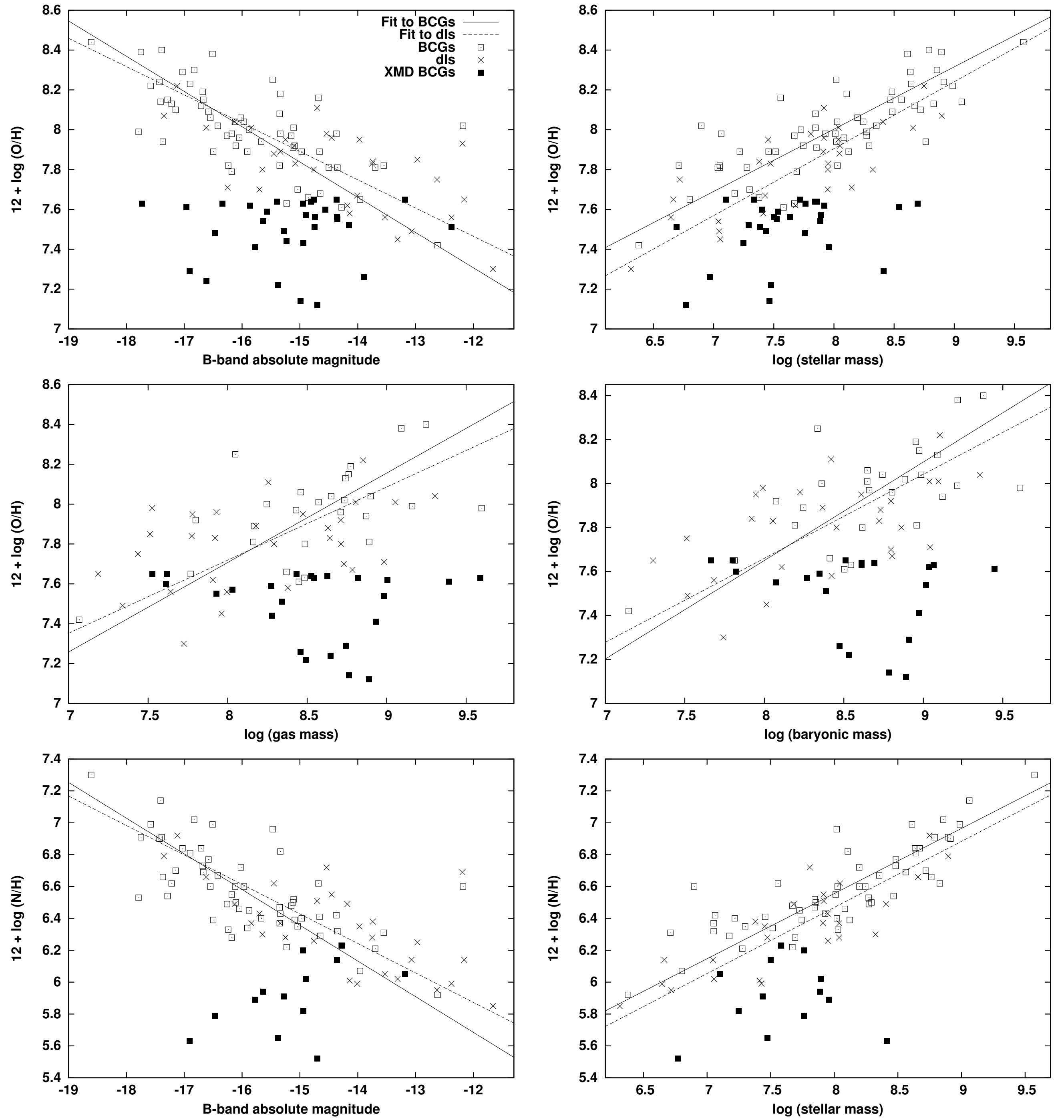

Figure 1. The derived correlations of B-band luminousity **(top left)**, stellar mass **(top right)**, gas mass **(middle left)**, baryonic mass **(middle right)** with oxygen abundance, and B-band luminousity **(bottom left)** and stellar mass **(bottom right)** with nitrogen abundance, for BCGs (solid) and dIs (dashed) are shown. The BCG, dI and XMD BCG data are represented by empty squares, crosses and filled squares, respectively.

[where the yield (p) is defined as the amount of metals produced, per unit mass that is locked up in stars, see, e.g., Binney & Merryfield (1998)]. Galaxies may not evolve as closed boxes, either because they gain (pristine) material due to infall, or lose (enriched) gas through galaxy winds. The quantity p, in Equation 1, then represents the effective chemical yield ($p_{\rm eff}$),

$$p_{\rm eff} = -Z/\ln(\mu_{\rm gas}), \tag{2}$$

of a galaxy.

As can be seen from the definition, $p_{\rm eff}$ depends on the metallicity and the gas mass fraction. In Fig. 4(top), we show the gas mass fraction of our sample of galaxies. As can be seen, XMD galaxies tend to be somewhat gas-richer than BCG or dI galaxies. The sample mean $\mu_{\rm gas}$ of the three sam-

$12 + \log(O/H) = (-0.177 \pm 0.016)\ M_B + (5.18 \pm 0.25)$	58 BCGs
$12 + \log(O/H) = (-0.142 \pm 0.019)\ M_B + (5.76 \pm 0.28)$	32 dIs
$12 + \log(O/H) = (0.313 \pm 0.025)\ \log(M_*) + (5.50 \pm 0.20)$	59 BCGs
$12 + \log(O/H) = (0.336 \pm 0.038)\ \log(M_*) + (5.22 \pm 0.29)$	30 dIs
$12 + \log(O/H) = (0.449 \pm 0.070)\ \log(M_{gas}) + (4.12 \pm 0.60)$	27 BCGs
$12 + \log(O/H) = (0.367 \pm 0.060)\ \log(M_{gas}) + (4.78 \pm 0.50)$	30 dIs
$12 + \log(O/H) = (0.448 \pm 0.065)\ \log(M_{bary}) + (4.07 \pm 0.56)$	27 BCGs
$12 + \log(O/H) = (0.382 \pm 0.060)\ \log(M_{bary}) + (4.60 \pm 0.26)$	28 dIs
$12 + \log(N/H) = (-0.224 \pm 0.019)\ M_B + (3.00 \pm 0.32)$	56 BCGs
$12 + \log(N/H) = (-0.185 \pm 0.021)\ M_B + (3.65 \pm 0.32)$	28 dIs
$12 + \log(N/H) = (0.409 \pm 0.028)\ \log(M_*) + (3.28 \pm 0.22)$	56 BCGs
$12 + \log(N/H) = (0.415 \pm 0.044)\ \log(M_*) + (3.15 \pm 0.34)$	26 dIs

Table 4. Derived L–Z and M–Z correlations

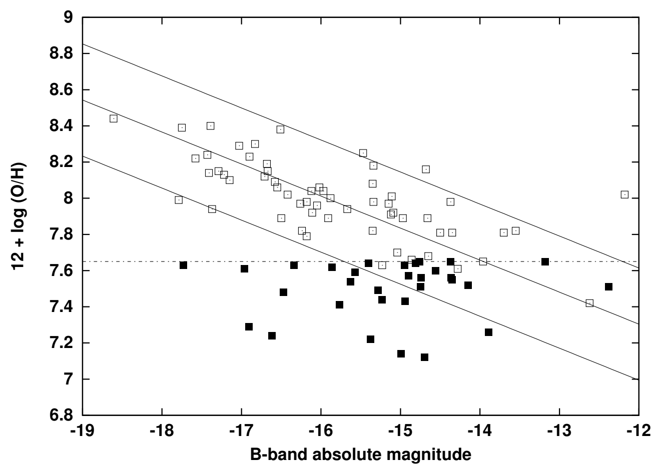

Figure 2. BCG (empty squares) and XMD (filled squares) galaxies data points are plotted in the L–Z plane. The best-fitting regression line to the BCG galaxies is shown, along with the 95 per cent confidence interval about this line. The dividing line between XMD and non-XMD galaxies [$12 + \log(O/H) = 7.65$] is also shown.

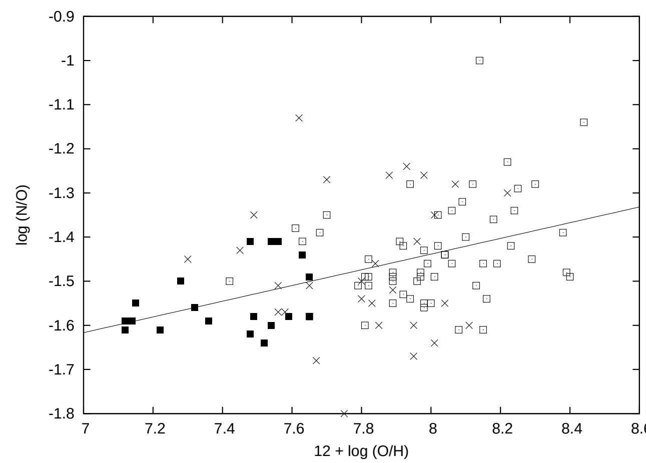

Figure 3. The nitrogen to oxygen ratio [log(N/O)] as a function of the oxygen abundance $12 + \log(O/H)$. The symbols are BCGs (empty squares), dIs (crosses) and XMD BCGs (filled squares). For XMD galaxies in which individual H II region metallicities are known, each is shown as a separate point. These are taken from Izotov et al. (2005), Izotov et al. (2009), Izotov et al. (2006a), Izotov et al. (2004), Izotov & Thuan (1999), Izotov, Thuan & Lipovetsky (1997), Guseva et al. (2003a), Guseva et al. (2003b), Lee et al. (2004) and Melbourne et al. (2004). The best-fitting line (i.e., linear regression) to a combined sample, including BCGs in our normal sample and H II regions of XMD BCGs (i.e., both empty and filled squares) is plotted.

ples are 0.74 ± 0.03 (BCG), 0.75 ± 0.03 (dI) and 0.82 ± 0.03 (XMD). Interestingly, the most discrepant XMD galaxies (i.e., those which lie below the 95 per cent confidence interval determined above) tend to have the highest gas fractions. The fact that XMD galaxies have larger gas mass fractions means that they have converted a smaller fraction of their baryonic mass into stars, and as such, one would expect them to have lower metallicities. If this was the only reason for their low metallicities, then XMD galaxies would have effective yields comparable to those of other gas-rich dwarf galaxies. Fig. 4(middle) shows the effective yield as a function of the gas mass fraction. One can see a clear separation between XMD and the other dwarf galaxies – at the same gas mass fraction, XMD galaxies have systematically lower effective yields. So clearly, there is some other phenomenon at work – perhaps, XMD galaxies have lost more of their metals via preferential outflow of metal-enriched gas? One would expect that the outflow of metal-enriched gas would increase with decreasing depth of the dark-matter halo potential of a galaxy. Following Tremonti et al. (2004), we use the baryonic mass as a proxy for the mass of dark matter [since the two are expected to be tightly correlated, because of the baryonic Tully-Fisher relation (McGaugh 2005)]. Fig. 4(bottom) shows the effective yield as a function of the baryonic mass. As can be seen, one does indeed see an increase in the effective yield with baryonic mass (the correlation coefficient computed for the BCG and dI samples is 0.54 ± 0.10, with the error bar computed via bootstrap resampling). However, what is interesting to note is that *at the same baryonic mass*, XMD galaxies have systematically lower effective yields than BCG or dI galaxies. Clearly again, some other process is at work in XMD galaxies.

In this context, it is interesting to note that H I studies of XMD BCGs (van Zee et al. 1998; Chengalur et al. 2006; Ekta et al. 2006, 2008, 2009; Ekta & Chengalur 2010) have shown that interactions/mergers are common in them. Recall that a fundamental assumption in deriving the effective yield is that the gas is *well-mixed*, i.e., any metals formed during star formation are uniformly mixed throughout the gaseous envelope. This is unlikely to be true in extremely gas-rich dwarf galaxies, where the gas disc is substantially

more extended than the stellar disc (Begum et al. 2008). This means that for these galaxies, if the effective yield is derived assuming that there is perfect mixing of all the gas, it will lead to an overestimate of the true yield. Note that in Fig. 4 (middle and bottom), the observed effective yields for BCGs and dI galaxies exceed the theoretically-computed closed-box yield [viz., an effective yield of 0.0074, i.e., log(p_{eff}) of –2.13 (Meynet & Maeder 2002)] while those of XMD galaxies are generally lower than this. In the absence of the infall of chemically-enriched gas, the closed-box yield is the maximum possible effective yield. Given the uncertainties in the theoretical calculations of the chemical yield and measurement errors, this can not be regarded as definitive evidence that the effective yields of gas-rich galaxies are overestimated if one includes the entire gas mass in the $p_{\rm eff}$ calculation, but it is certainly consistent with this idea.

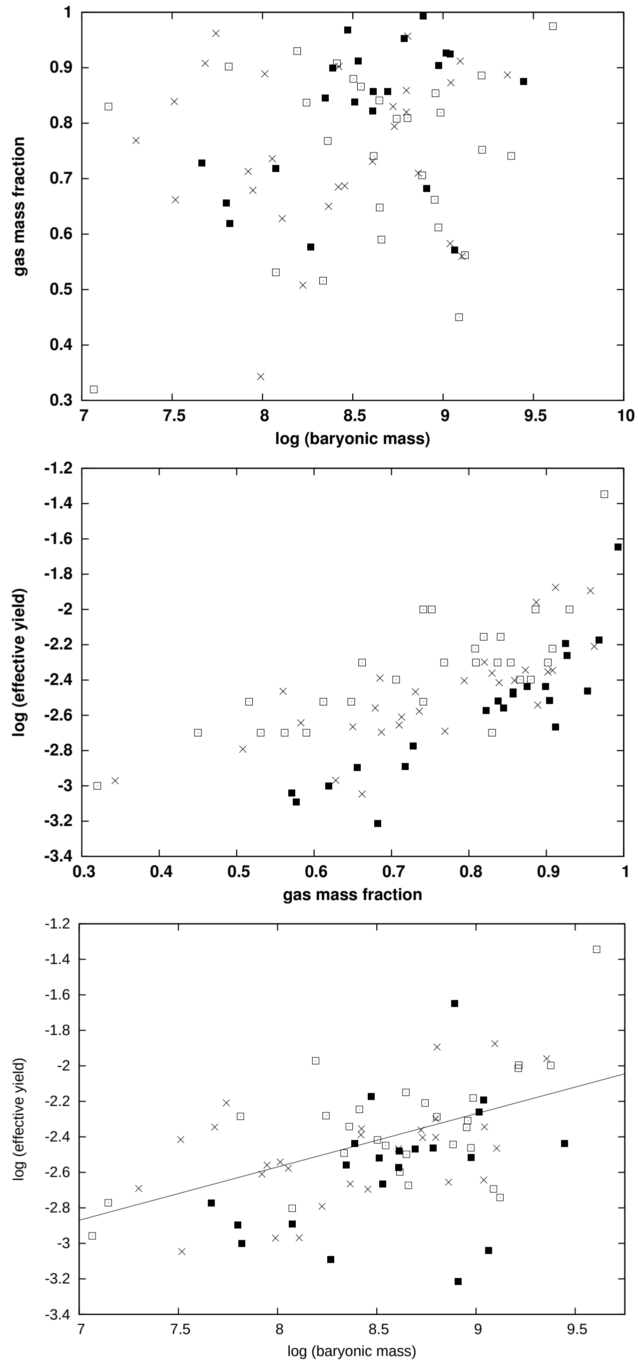

Figure 4. Gas mass fraction is plotted against baryonic mass **(top)**, and effective yield is plotted against gas mass fraction **(middle)** and baryonic mass **(bottom)** for BCGs (empty squares), XMD BCGs (filled squares) and dIs (crosses). The best-fitting line (i.e., linear regression) to the combined BCG and dI sample (XMD BCGs were not included) is shown in the bottom panel.

4 DISCUSSION & SUMMARY

There are, in principle, three possible reasons for the low metallicity of an XMD galaxy, viz., (i) low star formation efficiency, (ii) an outflow of metal-enriched gas, or (iii) an inflow of metal-poor gas. In disentangling these possibilities, it is useful to look at the effective chemical yields of the galaxies. Brooks et al. (2007) argue that low star formation efficiency of low-mass galaxies is primarily responsible for the M–Z relation. On the other hand, if the low metallicity were merely a consequence of low star formation efficiency, then all galaxies would have the same effective yield, which, as we saw in the previous Section, is not the case. Further, as can be readily shown (see, e.g., Dalcanton 2007) inflow of metal-poor gas can not substantially lower the effective yield of extremely gas-rich galaxies – for such galaxies, the effective yield asymptotes to a constant value ($M_Z/M_{\rm star}$) independent of the gas mass. Since most of our XMD galaxies are very gas-rich, it seems unlikely that their low metallicities are due to inflow of pristine material. Another possibility is an outflow of metal-enriched gas.

Numerical simulations (e.g., Maclow & Ferrara 1999) suggest that dwarf galaxies can lose a substantial fraction of their metals due to outflows driven by supernova explosion. The amount of metal loss, however, depends on both, the supernova rate and the spatial and temporal correlation of the explosions, and other simulations (e.g., Fragile, Murray & Lin 2004) indicate a much lower metal loss from dwarf galaxies. On the observational front, Tremonti et al. (2004) argue that the metal loss does, indeed, anti-correlate with the depth of the gravitational potential well (or equivalently, the effective yield correlates with the total baryonic mass) as would be expected in the outflow scenario. As we saw in the previous Section, a similar trend is seen in our samples of dwarf galaxies. On the other hand, Fig. 4 also shows that *at the same baryonic mass*, XMD galaxies have lower effective yields than other gas-rich dwarf galaxies. It, thus, appears that some process, particular to XMD galaxies, is responsible for their low metallicity.

Motivated by the observation that many of the XMD galaxies, with detailed H I observations, are undergoing interactions (e.g., Ekta et al. 2008), we propose that (other than being gas-richer, as seen in the previous Section) the mechanism responsible for the metal-deficiency of XMD galaxies is *a better mixing* of the ISM, as compared to the isolated, gas-rich dwarf galaxies. A similar argument was presented by Peeples, Pogge & Stanek (2009), who found that metal-poor outliers from the M–Z relation of star-forming galaxies have disturbed morphologies. They argued that this is a consequence of tidally-induced inflow of gas to the galax-

ies' central regions, where low-metallicity gas, from large galactocentric radii, dilutes the central, metal-rich gas. A similar result, as that of the XMD galaxies being preferentially found in the interacting pairs, was also found by Kewley, Geller & Barton (2006). They show that at the same luminousity, close galaxy pairs have systematically low metallicity, compared to wide pairs and field galaxies. Further, Lee et al. (2004) found that galaxies with disturbed morphologies are offset towards higher luminousity and low metallicity in L–Z plane, and argue that this could be a consequence of the mixing of outer, metal-deficient gas with the ISM surrounding the central star-forming regions.

Numerical simulations, presented by Bekki (2008), show the formation of BCD galaxies from merging between very gas-rich dwarf galaxies. They also show that since new stars can be formed in the centre of BCD galaxies, from the gas transferred from the outer part of the merger progenitors, new stars can be very metal-poor. More recently, Rupke, Kewley & Barnes (2010) presented an analysis of simulations of mergers, which confirm that nuclear metallicity underabundances, observed in interacting disc galaxies, are due to merger-driven inflow of low-metallicity gas from the outskirts of merging galaxies. A subsequent analysis of gas-rich interaction and mergers by Montuori et al. (2010) shows a strong trend between the star-formation rate and dilution of metals in the nuclear region, due to inflows of metal-poor gas from the outer regions of merging discs, which fuels the intense star formation and lowers the metallicity. Finally, additional support to the idea, that the ISM in XMD galaxies is well-mixed, comes from Far Ultraviolet Spectroscopic Explorer (FUSE) observations of BCD galaxies which show that, in general, the neutral gas is more metal-poor as compared to the ionised gas in the H II regions. In the most metal-deficient galaxies, however, the two are comparable (Lebouteiller et al. 2009 and references therein).

It is worth emphasizing that in the scenario being suggested here, it is not so much that XMD galaxies have low chemical yields, as that the effective yields of isolated, gas-rich dwarf galaxies are overestimated. This overestimate is because the gas in the outer parts of the galaxy (which generally lies well outside the stellar disc, and does not participate in star formation) is, none the less, included in the calculation of effective yield. Better mixing of the gas, however, would not only lower the metallicity in the central star-forming regions, but also bring the galaxy closer to the well-mixed assumption in the closed box model, and hence, decrease the overestimation of the yield. We can now return to one of the questions that we had set ourselves at the start of this paper, viz., do XMD galaxies represent a separate population, or are they merely the low-metallicity tail of the metallicity distribution of galaxies? The conclusion that we reach is that they do indeed seem to be a separate population, one in which tidal interactions have led to a lower metallicity via a better mixing of the ISM.

To summarise, we try to address the question that whether the metallicities of XMD galaxies are consistent with those expected from the luminousity–metallicity and mass-metallicity relations of other gas-rich dwarf galaxies, or are XMD galaxies discrepant. To answer this, we consider the properties of three samples of galaxies, viz., a sample of XMD galaxies and comparison samples of BCGs and dI galaxies. We enlist our conclusions below.

(i) For sufficiently low-luminousity (i.e., $M_B > -15.7$) galaxies, a metallicity of 12 + log (O/H) $\sim$ 7.65 (i.e., the threshold metallicity for XMD galaxies) is consistent with what one would expect from the luminousity–metallicity relation.

(ii) The lower bound to the 95 per cent confidence interval, around the L–Z relation, is given by Z = $-0.177\ M_B + 4.87$. We suggest that this would be a more appropriate definition for XMD galaxies. As per this definition, 17 of the 31 galaxies, in our sample, would be identified as XMD.

(iii) As shown in previous work, we find that the L–Z relation of BCGs is shifted to higher luminousities at a given metallicity, compared to dIs. This has been considered as an evidence for the fact that the luminousity of BCGs is temporarily enhanced due to ongoing starburst. Consistent with this suggestion, we find that the M–Z relations of our BCG and dI samples are better matched.

(iv) The effective chemical yields of XMD BCGs are systematically lower than BCGs and dI galaxies, with similar gas fractions and baryonic masses. We suggest that this is because of better mixing of the ISM in the case of XMD galaxies, as compared to other gas-rich dwarf galaxies. Motivated by the observation that many XMD galaxies are interacting (Ekta et al. 2008) we suggest that the better mixing is due to tidal interactions. We propose that XMD galaxies deviate from the L–Z and M–Z relations because of a combination of having low effective chemical yields and higher gas fractions.

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